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TOWARDS THE DEVELOPMENT OF A MANAGEMENT PLAN FOR THE MACKEREL ICEFISH (*CHAMPSOCEPHALUS GUNNARI*) IN SUBAREA 48.3

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Abstract

Management of the mackerel icefish (*Champsocephalus gunnari*) at South Georgia is complicated by the likelihood of substantial periodic variations in natural mortality rates. These may be associated with increased consumption of *C. gunnari* by Antarctic fur seals in years of poor krill availability. Thus natural mortality of *C. gunnari* may, in some years, increase by a large factor (assumed here to be 4), declining to normal levels again when krill return. This paper outlines a scheme which would use information from studies on krill and predators undertaken as part of the CCAMLR Ecosystem Monitoring Program (CEMP) to interpret or modify information from commercial fisheries and research surveys leading to estimates of stock biomass. An extension of this scheme would use predictions of coming periods of krill scarcity as early warnings of increased natural mortality of *C. gunnari*.

Full implementation of such a scheme would require greater knowledge of quantitative aspects of food web dynamics within the South Georgia ecosystem than we possess at present. There is therefore a need for an interim approach to the setting of precautionary catch limits for this fishery. An approach based on the CCAMLR generalised yield model (GYM), with periodically varying natural mortality, provides a realistic description of perceived icefish dynamics. However, the model generates a significant probability that *C. gunnari* populations will be depleted even in the absence of fishing, which, given the existing CCAMLR decision rules, would preclude the fishery's ever opening. Several possible modifications to the decision rules are discussed. It is concluded that while the GYM can be used to estimate a temporary, conservative long-term yield, a new approach and set of decision rules will ultimately be required for *C. gunnari*.

Résumé

La gestion du poisson des glaces (*Champsocephalus gunnari*) en Géorgie du Sud est compliquée par l'existence probable de variations périodiques importantes des taux de mortalité naturelle. Ces variations peuvent être associées à l'accroissement de la consommation de *C. gunnari* par les otaries de Kerguelen les années où le krill se fait rare. La mortalité naturelle de *C. gunnari* peut donc, certaines années, être de plusieurs fois plus importante (il est supposé ici qu'elle est de 4 fois plus importante) pour redescendre à des niveaux normaux au retour du krill. Le présent document décrit un système permettant d'utiliser les informations dérivées des études sur le krill et les prédateurs menées dans le cadre du Programme de contrôle de l'écosystème de la CCAMLR (CEMP) pour interpréter ou modifier les informations des pêcheries commerciales et des campagnes d'évaluation de recherche utilisées pour estimer la biomasse du stock. En développant davantage ce système, on pourrait utiliser les prévisions indiquant les périodes où le krill sera rare comme signes précurseurs de l'accroissement de la mortalité naturelle de *C. gunnari*.

Pour pouvoir appliquer pleinement ce système, il serait nécessaire d'approfondir notre connaissance des aspects quantitatifs de la dynamique du réseau trophique de l'écosystème de la Géorgie du Sud. Pour cette raison, il convient d'adopter, pour fixer les limites préventives de capture de cette pêcherie, une approche provisoire telle que celle qui est fondée sur le modèle de rendement généralisé (GYM) de la CCAMLR, avec une mortalité naturelle variant périodiquement, afin d'obtenir une description réaliste de la dynamique connue du poisson des glaces. Pourtant, ce modèle engendre une grande probabilité que les populations de *C. gunnari* soient épuisées même en l'absence de toute pêche, ce qui, vu les critères de décision retenus par la CCAMLR, empêcherait à tout jamais l'ouverture de la pêcherie. La discussion porte sur plusieurs modifications qu'il serait possible d'apporter aux critères de décision. En conclusion, il apparaît qu'alors que le GYM permette d'estimer un rendement temporaire favorable à la conservation à long terme, il faudra tout de même mettre en place une approche et une série de critères de décision spécifiques à *C. gunnari*.

Резюме

Управление промыслом ледяной рыбы (*Champsocephalus gunnari*) в районе Южной Георгии усложняется вероятностью существенных периодических изменений в естественной смертности этого вида. Возможно, что эти изменения связаны с более интенсивным потреблением *C. gunnari* южными морскими котиками в годы низкого наличия криля. Следовательно в некоторые годы имеется возможность того, что естественная смертность *C. gunnari* увеличится в несколько раз (здесь предполагается четырехкратное увеличение), а затем снизится до нормального уровня, когда криль вновь появляется в достаточном количестве. В данной работе описывается метод получения оценок биомассы запаса, согласно которому используется информация, полученная в результате исследований криля и хищников в рамках Программы АНТКОМа по мониторингу экосистемы (СЕМР), для интерпретации или модифицирования информации, полученной в результате коммерческого промысла и научно-исследовательских съемок. В соответствии с этим методом прогнозы наступающих периодов низкого наличия криля могут послужить сингналом повышенной естественной смертности *C. gunnari*.

Для надлежащего применения этого метода потребуется больше сведений о количественных аспектах динамики трофической цепи экосистемы Южной Георгии, чем мы располагаем сегодня. Поэтому для данного промысла необходим промежуточный подход к установлению предохранительных ограничений на вылов. Подход, основанный на разработанной в АНТКОМе обобщенной модели вылова (GY-модели), учитывающий периодически изменяющуюся естественную смертность, дает реалистичное описание динамики ледяной рыбы. Однако в связи с тем, что с данной моделью связана большая вероятность истощения популяций *C. gunnari* - даже в отсутствии промысла, существующие правила принятия решений исключают возможность того, что в будущем промысел снова откроется. Обсуждается ряд возможных изменений к правилам принятия решений. Делается вывод, что хотя для рассчета временного, предохранительного долгосрочного вылова можно использовать GY-модель, в конечном итоге необходимо разработать новый подход и новые правила принятия решений для управления промыслом *C. gunnari*.

Resumen

La ordenación del recurso draco rayado (*Champsocephalus gunnari*) en Georgia del Sur se ve complicada por la probabilidad de grandes variaciones periódicas de las tasas de mortalidad natural. Estas variaciones pueden estar relacionadas con el aumento del consumo de *C. gunnari* por el lobo fino antártico en años de escasez de kril. Es así como la mortalidad natural de *C. gunnari* puede, en algunos años, aumentar en un factor considerable (en este estudio se supone que el factor es cuatro), y luego disminuir al nivel normal cuando el kril vuelve a estar disponible. Este estudio describe un esquema que utilizaría la información de los estudios sobre el kril y los depredadores que se realizan en el programa de seguimiento del ecosistema de la CCRVMA (CEMP) para interpretar o modificar la información de las pesquerías comerciales y de las prospecciones de investigación, y poder así efectuar estimaciones de la biomasa del stock. Una aplicación de este esquema utilizaría la predicción de próximos períodos de escasez de kril como una indicación temprana del aumento de la mortalidad natural de *C. gunnari*.

La aplicación plena de tal esquema requeriría de un mayor conocimiento del que se posee actualmente sobre los aspectos cuantitativos de la dinámica de la cadena alimenticia en el ecosistema de Georgia del Sur. Por lo tanto, se necesita un enfoque provisional para fijar los límites de captura precautorios en esta pesquería. El enfoque basado en el modelo de rendimiento generalizado de la CCRVMA (GYM), que toma en cuenta las variaciones periódicas de las tasas de mortalidad natural, proporciona una descripción realista de la percepción actual de la dinámica del draco rayado. Sin embargo, el modelo origina una probabilidad significativa de que las poblaciones de *C. gunnari* se agoten aún cuando no exista explotación, y según los criterios de decisión actuales de la CCRVMA, esto impediría para siempre la apertura de la pesquería. Se discuten varias posibles modificaciones a los criterios de decisión. La conclusión es que aún cuando el modelo GYM puede ser utilizado para la estimación provisional de un rendimiento prudente a largo plazo, en última instancia se necesitan nuevos enfoques y criterios de decisión para *C. gunnari*.

Keywords: icefish, population dynamics, fisheries management, South Georgia, yield, ecosystem, CCAMLR

INTRODUCTION

Management of the mackerel icefish (*Champsocephalus gunnari*) at South Georgia poses several unique problems, largely due to the position of this fish in the food web. A commercial fishery existed in Subarea 48.3 in the 1970s and 1980s, ceasing in March 1990 (Kock, 1992). The most recent stock assessment was performed at the 1993 meeting of CCAMLR's Working Group on Fish Stock Assessment (WG-FSA). Since then Everson et al. (1994a) have suggested that marked declines in stock biomass in some years were unlikely to be the result of commercial fishing pressure. Rather, they may have been associated with increased predation by fur seals in years of krill scarcity. This suggests periodic variations in natural mortality which are larger than usually experienced by fish stocks and which may or may not be predictable. The possibility of major ecosystem interactions, and the resulting uncertainty about stock trajectories, has been a factor in the Scientific Committee's suspension of its routine stock assessments. It led to a request for the development of a long-term management plan for *C. gunnari* in Subarea 48.3 (SC-CAMLR, 1994a – paragraphs 2.34 to 2.38).

Surveys directed at *C. gunnari* are extremely useful for determination of the status of the stock, and comparable survey series have been used in the past to tune VPAs (Parkes, 1993). It is clear, however, that if natural mortality (M) is highly variable from year to year, it is difficult to make long-term predictions from surveys. Thus there is presently no accepted method of performing assessments that might lead to a scientifically derived TAC. In the last two seasons (1995/96 and 1996/97), in the absence of an acceptable assessment of stock status, TACs have been set at levels that would appear *a priori* to be very conservative.

This paper is divided into two sections. The first explores the possibility of developing a feedback assessment approach based on information from the fishery, trawl surveys, predators and the environment, which will provide the outputs required for management of *C. gunnari* in Subarea 48.3. The second develops a method of calculating potential yield for *C. gunnari* which could be used in the interim while the feedback approach is being developed, a process that is expected to take several years.

DEVELOPMENT OF A MANAGEMENT PLAN FOR *C. GUNNARI*

The data and information requirements for the development of a long-term management plan were considered in some detail at the 1996 meeting of WG-FSA. Here WG-FSA's discussions are extended to include an indication of how information from the CCAMLR Ecosystem Monitoring Program (CEMP) might be used to provide information about recent levels of natural mortality (M) and likely future trends.

Champsocephalus gunnari in the South Georgia Food Web

Everson et al. (1994a) postulated that *C. gunnari* exists within a dynamic set of trophic interrelationships (Figure 1) whose particular configuration is mediated by local krill abundance. Krill are the preferred food of both *C. gunnari* and fur seals and the latter also eat fish, including *C. gunnari* (Kock et al., 1994; North, 1996; Reid and Arnould, 1996). During the fur seal breeding season, both *C. gunnari* and female fur seals are restricted to foraging for their krill in the vicinity of South Georgia. The abundance of krill at South Georgia is variable, however. In most years krill is present in very large quantities, but periodically its abundance is low.

Surveys undertaken in the early 1990s detected large declines in the *C. gunnari* population in the years 1990/91 and 1993/94 (surveys were undertaken in February/March 1991 and 1994 – Everson et al., 1991, 1994b). Since catches in these years were 183 and 0 tonnes respectively, the declines cannot have been due to fishing. 1990/91 and 1993/94 were also years of low krill abundance (SC-CAMLR, 1994b – paragraph 4.73; Brierley et al., 1997). The possibility of a link between years of poor krill availability and reduced *C. gunnari* abundance was noted by WG-FSA in 1994.

What could cause the increased mortality of *C. gunnari* in years of low krill abundance? Everson et al. (1994a) noted declines in the condition factor of *C. gunnari* in 1991 and 1994, and found that a greater proportion of their diet was made up of *Themisto gaudichaudii* in these years. More recent analyses have suggested that the declines in condition factor were unlikely to have been of sufficient magnitude to give rise to major increases in natural mortality (Everson et al., 1997). Thus *C. gunnari* may not be dying simply because they cannot find enough food.

Another explanation put forward by Everson et al. (1994a, 1998) is that when krill are scarce, predators might increase the proportion of *C. gunnari* in their diet. They point out that there are two major predators of *C. gunnari* around South Georgia: gentoo penguins and fur seals. The gentoo penguin population is estimated to consume about 28 000 tonnes of fish each year, of which about 7 500 tonnes is *C. gunnari* (Croxall et al., 1984, 1997). Everson et al. (1998) do not consider that this predator is able on its own to account for the declines in *C. gunnari* abundance. On the other hand, the population of fur seals at South Georgia has increased rapidly in recent years, to 4 million animals. Fur seal consumption of *C. gunnari* in both good and poor krill years is well documented (Reid, 1995; North, 1996; Reid and Arnould, 1996). Using data from published models of fur seal energetics, Everson et al. (1998) estimate that fur seals could consume 5 or 6 million tonnes of krill each year and, if they were forced to feed exclusively on fish, might consume over 4.5 million tonnes. A shift of less than 5% in fur seal diet from krill to fish could effectively reduce the *C. gunnari* stock to extremely low levels.

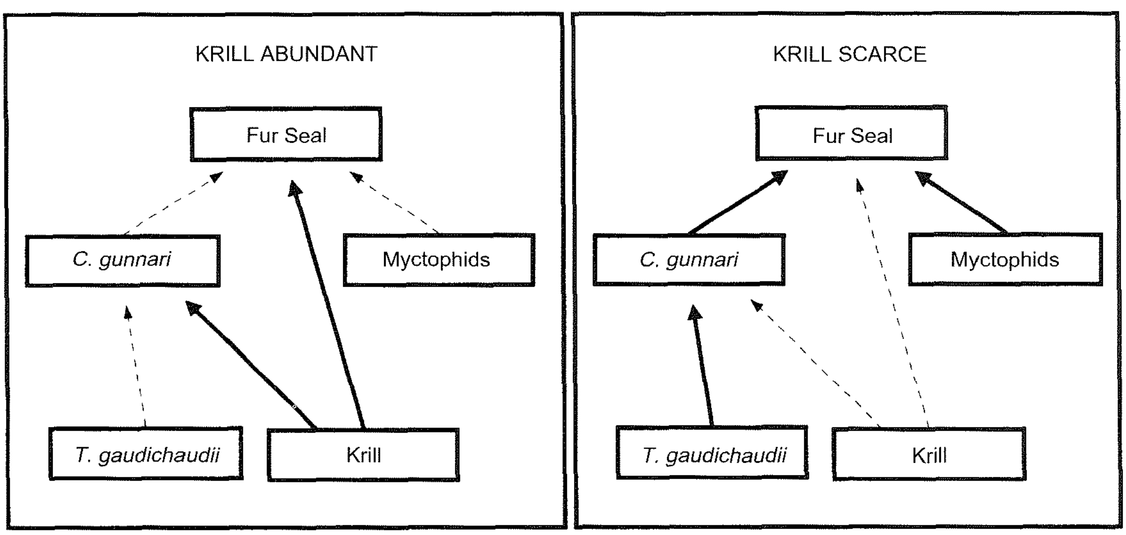

Figure 1: Schematic representation of the South Georgia *Champsocephalus gunnari* food web under conditions of krill abundance and scarcity.

C. gunnari may therefore encounter two problems in years of low krill abundance, consequent dependence for food on another plankton crustacean, *T. gaudichaudii*, and increased predation by fur seals and other predators, the effects of these two events being additive. In other words, when krill are scarce there are likely to be some shifts in the food web dynamics, as suggested by Figure 1, which might periodically increase the natural mortality of *C. gunnari*.

The exact nature of these changes, particularly the quantitative aspects, is at present uncertain. Composite indices of predator performance at South Georgia compiled by the CCAMLR Working Group on Ecosystem Monitoring and Management (WG-EMM) in 1997 (SC-CAMLR, 1997b) identify 1978, 1984, 1991 and 1994 as being poor years for predators (these indices reflect predator performance from January to March of the stated year). But the extent of predator success varies considerably between years, indicating perhaps that krill scarcity is also variable. The amount of krill present at any one time is thought to be controlled by two factors:

(i) the amount of krill carried in the Antarctic Circumpolar Current (ACC) across the Scotia Sea from the South Shetlands and Weddell Sea; and

(ii) the location of the Antarctic Polar Frontal Zone (APFZ).

The amount being carried in the ACC will be controlled by the production of krill in localities upstream of South Georgia. The location of the APFZ is controlled by the Southern Ocean circulation and weather systems (Trathan et al., 1997). Both of these are being actively researched with particular reference to the management of the krill fishery (SC-CAMLR, 1997a). Some ability to predict krill occurrence at South Georgia (at least over short time periods such as several months) might therefore be expected in the next few years.

The hypothesis that increased consumption of *C. gunnari* by fur seals in years of low krill abundance is directly responsible for a reduction in *C. gunnari* stocks is attractively simple. However, we need much better data on the relationship between krill abundance, consumption rates by *C. gunnari* and fur seals and the nature and magnitude of diet switching in these species under different conditions in order to be able to rigorously test the hypothesis. In addition, the behaviour of *C. gunnari* and seals may be of importance. For example, *C. gunnari* are known to form large dense aggregations on the South Georgia shelf at certain times. These aggregations may persist for periods of at least a few months. At other times the fish appear to be more dispersed. It may be that only when the fish are aggregated into concentrated patches are they sufficiently available to fur seals to allow for the rate of consumption required to give rise to the observed periodic declines in abundance. The timing of the patches would therefore need to coincide with the foraging periods of the fur seals. Expressing fur seal predation as a proportion (such as M) is therefore more appropriate than discussing absolute consumption estimates at this stage. Nevertheless any estimate must be regarded as very provisional.

Potential Data Sources for the Management Plan

The long-term management plan for *C. gunnari* will need as its cornerstone an assessment of the status and future potential of the resource. Estimates of *C. gunnari* biomass have come from two sources in the past: analysis of research survey results and analysis of commercial catch-at-age using VPA (tuned to surveys and CPUE). Since 1990/91 the only data available have been from research surveys.

Trajectories of biomass are required for the determination of future potential yield. However, the usual difficulties in predicting likely trajectories in biomass based on survey results (i.e. uncertainties in the precision of survey results and the relationship between survey and absolute biomass) are exacerbated by the uncertainties in M associated with ecosystem interactions at South Georgia (Figure 1). The various sources of information which might contribute to the assessment of the current biomass and future potential yield of *C. gunnari* are listed and reviewed below.

1. Targeted surveys:

    (i) currently the best method of providing information on standing stocks;

    (ii) provide the most up-to-date information on standing stocks at the time of the survey, but uncertainty in subsequent variations in natural mortality progressively reduces the validity of the estimates as time since the survey increases; and

(iii) juvenile and larval fish surveys might provide information on potential recruitment.

2. Water-mass circulation with particular reference to krill distribution and standing stock:

   (i) analysis of sea-surface temperature information may provide indications of the location of the APFZ and consequently of the likelihood of a continued supply of krill to the region. (This linkage is still the subject of investigation by WG-EMM); and

   (ii) information from 'upstream' locations, such as the South Shetlands, could provide a warning of a possible period of krill scarcity some months later at South Georgia.

3. Monitoring of krill and *C. gunnari* predators (fur seals and gentoo penguins):

   (i) provides estimates of likely total food consumption (krill and fish) based on population size and energy requirements;

   (ii) although quantitative estimates of the relative proportions of krill and fish are very difficult to obtain at present for seals, future research might permit the absolute quantity of *C. gunnari* consumed by fur seals to be estimated, at least in some seasons. This would greatly assist in the assessment of *C. gunnari* natural mortality rates, and changes therein; and

   (iii) the existing monitoring of seals and seabirds already provides indicators of the occurrence of a year of low krill abundance, of use in developing future management measures. Insights into *C. gunnari* trophic dynamics are also obtained from studies on species other than fur seals, for instance the relative importance of juvenile *C. gunnari* and krill in the diet of gentoo penguins.

4. Observations from the commercial fishery:

   (i) samples collected by observers, particularly on condition indices immediately prior to spawning, should provide information on the responses of *C. gunnari* to krill availability; and

   (ii) standard commercial fisheries data are likely to form one of the primary data sources for future assessments.

Towards a Sequence of Sampling, Analytical and Decision-making Processes

The outline of an approach for using these various sources of information in the development of advice in support of the *C. gunnari* management plan is given in Figure 2. The central approach, as with most fisheries assessments, would be to estimate current stock biomass and, from this, to calculate estimates of yield. Stock biomass would be assessed using traditional fisheries information: from the commercial fishery, from trawl surveys and from recruitment information. Running in parallel with this would be monitoring of krill availability and predator consumption of *C. gunnari* and krill. Information from predators and krill distribution would be used to infer the likely ranges of M in past and future years, which would be used when performing stock assessments using commercial or research information.

So far, this approach does not differ substantially from other approaches taken recently by CCAMLR, i.e. the setting of TACs based on assessments while using all available information to interpret the assessments. What may be different about the South Georgia case is that when the ecosystem is well enough defined it may prove possible to predict likely changes in natural mortality from year to year. These could be used to adjust the values of natural mortality used in any calculations of potential yield from estimated biomass. For instance, M for the coming year could be assumed to be 'normal' unless there are indications that krill is likely to be scarce, when high values of M could be used. It may also be that the age-distribution of M shifts in years of high fur seal predation, depending on the size of animals in the fur seal and *C. gunnari* populations. However, unless detailed data on age-specific mortalities were available, it would be sensible to assume flat M-selectivities for the purposes of population predictions.

It is recognised that development of a quantitative description of the functional dynamics in the South Georgia ecosystem may take some time. However, implementation of the

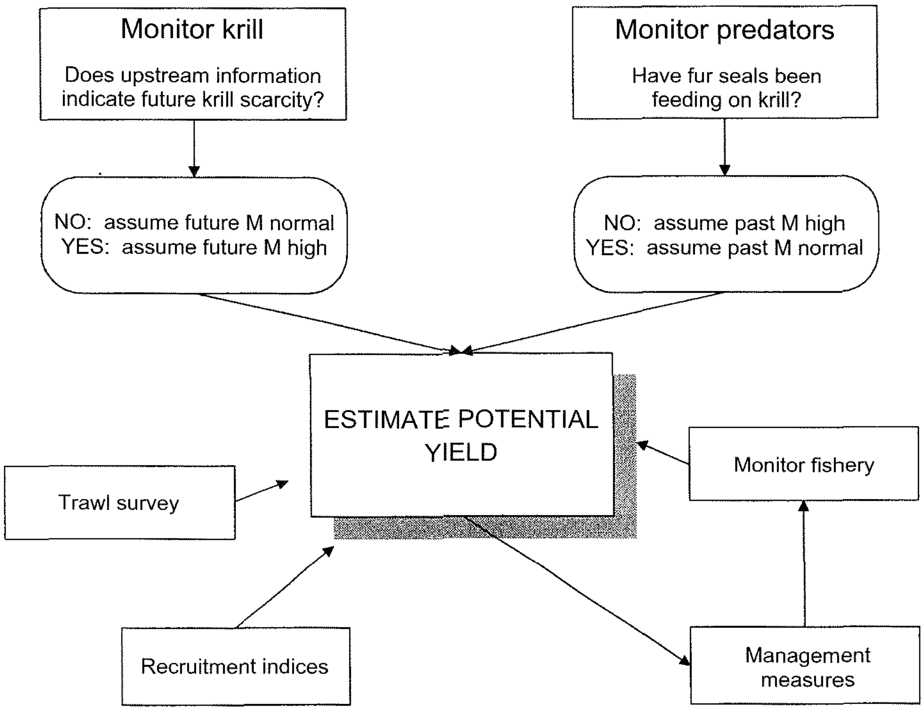

Figure 2: Assessments of potential yield of *Champsocephalus gunnari* are made using fisheries, survey and recruitment data. The mechanism for arriving at assessments may vary from the GYM approach to a VPA depending on information available. Assumptions about natural mortality to be used in assessments and projections from the assessments are adjusted according to information obtained from the monitoring of krill and predators.

system outlined in Figure 2 need not await a full description of the ecosystem. It could be used now, in a precautionary sense, to provide guidance on appropriate harvest rates. In the absence of information to the contrary, 'normal' natural mortality would be assumed to be very variable. Patterns of variability in *C. gunnari* natural mortality could be linked to existing data on predator performance in years where there is no evidence that krill is particularly scarce. As more information is acquired about the dynamic interactions in Figure 1, it might be possible to reduce this variability, only increasing natural mortality in years in which ecosystem studies suggest that this should be the case. Such a mechanism would produce conservative estimates of potential yield.

There remains a possibility that the declines observed in *C. gunnari* abundance in 1990/91 and 1993/94 were a result of unreported fishing effort or emigration events (SC-CAMLR, 1997c). Should the observed declines ultimately be demonstrated not to have been a result of increased natural mortality, mediated by predators or otherwise, the estimates of potential yield made using the system described above would still have been conservative.

INCORPORATING UNCERTAINTY IN NATURAL MORTALITY INTO CALCULATIONS OF *C. GUNNARI* POTENTIAL YIELD

Standard single-species approaches, such as yield/recruit analysis and the use of $F_{0.1}$, which have been used to determine *C. gunnari* TACs by CCAMLR in the past are clearly less-than-ideal methods to use for the management of *C. gunnari* in this highly variable, multi-species system. It is therefore highly appropriate that CCAMLR is seeking a new long-term management plan for *C. gunnari* in Subarea 48.3. However, given the time it is likely to take to complete this, it is useful to consider possible interim solutions. Along these lines it might be possible to determine some precautionary long-term yields using the CCAMLR generalised yield model (GYM) (Constable and de la Mare, 1996), which allows for the incorporation of many levels of uncertainty. Sufficient is known about the variability in the South Georgia system to suggest ranges for a number of the parameters. From this base level, and in the spirit of CCAMLR's precautionary approach, further understanding of the *C. gunnari* ecosystem would lead to either refinement of the GYM or development of more specific *C. gunnari* management models.

Table 1: Values of parameters used for the generalised yield program (version 2.01).

Category	Parameter	Value
Age composition	Recruitment age in simulation Number of age classes Plus class present – years in plus class in initial age structure	1 6 3
Resolution	Number of increments per year	360
Natural mortality	Mean annual M Interannual variability in M	0.42–0.54 0.2 probability of increase in M by 4
Fishing mortality	Length of fish when 50% recruited to the fishery Length range over which recruitment occurs Fishing season Reasonable upper bound for annual F Tolerance (error) for determining F	15–22 cm 5cm 15 November–31 March 5 1E5
von Bertalanffy growth	Time 0 L_∞ K	0 45.5 0.332
Weight–length ($W = aL^b$)	a b	1.8E-6 3.36
Spawning biomass	Length of fish when 50% are mature Range over which maturity occurs Spawning season	21–28 cm 10cm 1 March–30 April
Recruitment	Mean of ln(recruits) Standard error of the mean of ln(recruits) Standard deviation of ln(recruits)	20.1042 0.2397 0.8970
Evaluation of γ (ignored)	Date of biomass survey CV of biomass estimate Coverage of survey	1 September 0.3 1
Simulation characteristics	Number of runs in simulation for each catch Years to project stock to remove effects of initial age structure Vector of real catches for projecting over known catch period (tonnes) Number of years to project stock following known catch period Seed for random numbers	2001 1 0, 500, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000 10 Start (-24189): not reset each time
Decision rules	Reference point for assessment of long-term annual yield	$0.2.SB_0 median$

The following sections describe the input parameters and results of assessments carried out by means of a GYM on South Georgia *C. gunnari*. Table 1 presents the parameters that were used in the base case of the model. Version 2.01 of GY.EXE was used.

Duration of Projection

Because of the uncertainties not only in model parameters but in general system dynamics, the generalised yield approach should probably not be used as a basis on which to set a single, long-term yield for the fishery. Regular assessments of stock status would be required, certainly in the short term and probably in the long term. As in Figure 2, all sources of information would be used to review these assessments, and a new generalised yield calculation could be performed as appropriate. This feedback approach would ensure that gradual modifications to the scheme could be made as more qualitative and quantitative information became available.

With regular or annual reviews anticipated, we are concerned primarily with the probability of depletion in the short term. The oldest true age used for previous (VPA) assessments of this species by WG-FSA was age 5 (SC-CAMLR, 1993). Projections were therefore performed for twice this time, i.e. 10 years.

NATURAL MORTALITY

Following the discussion in the early part of this paper, we assume that the natural mortality rate for most years is at some 'normal' level, increasing several-fold in some years to produce periodic episodes of high mortality. We need to define what these two levels are likely to be.

The 'normal' natural mortality rate for *C. gunnari* was assumed by SC-CAMLR (1993) to be 0.48 yr^{-1}. The situation has recently been re-examined by SC-CAMLR (1997c) and Everson (1998). Based on the results of these reviews, we assume a range of 'normal' M of 0.42 to 0.54 yr^{-1} in the calculations presented in this paper, and conduct a sensitivity run with M of 0.44 to 0.52 yr^{-1}.

There are few data on the level of M in years of krill scarcity. Parkes (1993) estimated that M may have been as high as 2 or 3 yr^{-1} for fish aged 2 to 4 between January 1990 and January 1991, some four to six times its normal level. WG-FSA estimated similar levels between the 1992/93 season and January 1994 (SC-CAMLR, 1994b – paragraph 4.72). For the krill-scarce years 1978 and 1984 there are no survey estimates from which one could derive estimates of M, but the estimated standing stock on 1 July each year from the VPA (SC-CAMLR, 1993 – Figure 5) holds some clues. There is a decline in *C. gunnari* biomass following the period of krill scarcity in the summer of 1983/84, which would be consistent with a hypothesis of increased mortality. However, rather puzzlingly, there also appears to be a decline the previous year. There is no indication of a major decline in biomass between July 1977 and July 1978.

There is obviously some uncertainty about the range of M values expected in periods of krill scarcity. We therefore assume as our 'base case' that in years of krill scarcity natural mortality will increase by a factor of 4. We investigate the sensitivity of the results to this assumption by varying the factor from 3 to 5.

At present, whilst we believe that periodic episodes of high mortality occur, we cannot predict when they will happen. They are therefore assumed to be independent between years and equally likely to occur in each year. Results of a number of investigations suggest that in the last two decades at South Georgia there have been four years of assumed very low krill abundance. These were the summers of 1977/78, 1983/84, 1990/91 and 1993/94*. Although there is some evidence from SC-CAMLR (1997b) that there have been two further years of krill scarcity in the last decade, these were not as severe as the four noted above (J. Croxall, pers. comm.) and had an unknown impact on *C. gunnari* populations. We will therefore assume an approximate probability of encountering a year of krill scarcity of 0.2.

Recruitment

VPAs presented by the working group in 1993 (SC-CAMLR, 1993 – Figure 5) used M = 0.48 yr^{-1}. This is sufficiently close to recent estimates of M that the results can be considered to provide a fairly good history of the stock though they do not, of course, take account of any possible episodes of increased mortality. They will therefore be a conservative estimate of mean recruitment to the stock. The absolute level and log-normal distribution of recruitment was calculated from this VPA.

Biological Parameters and Catch Levels

All growth and other parameters are relatively well known, and were taken here from Kock et al. (1985) and Parkes (1993). The effects of constant catch in the GYM was examined explicitly rather than as a proportion γ of initial biomass. This removed the requirement for a survey estimate of biomass.

RESULTS

The results should be viewed in the light of CCAMLR's three-part decision rule for determining catch limits from stochastic models such as the GYM (SC-CAMLR, 1994a – paragraphs 5.18 to 5.26; SC-CAMLR, 1995a – paragraph 5.64):

(i) Rule 1: γ_1 is the catch level at which the probability of stock biomass dropping below 20% of its unexploited median level is 0.1;

(ii) Rule 2: γ_2 is the catch level at which the ratio of the median stock biomass after exploitation to the median stock biomass in the absence of fishing is 0.75; and

(iii) Rule 3: γ_3, the catch level adopted for a sustainable catch limit (or TAC), is the lower of γ_1 and γ_2.

* Predator indices: Croxall et al., 1988 and WG-EMM (SC-CAMLR, 1995b – Table 3.7; SC-CAMLR, 1997b); krill scarcity in 1977/78, Bonner et al. (1978), in 1983/84, Heywood et al. (1985) and in later years Brierley et al. (1997).

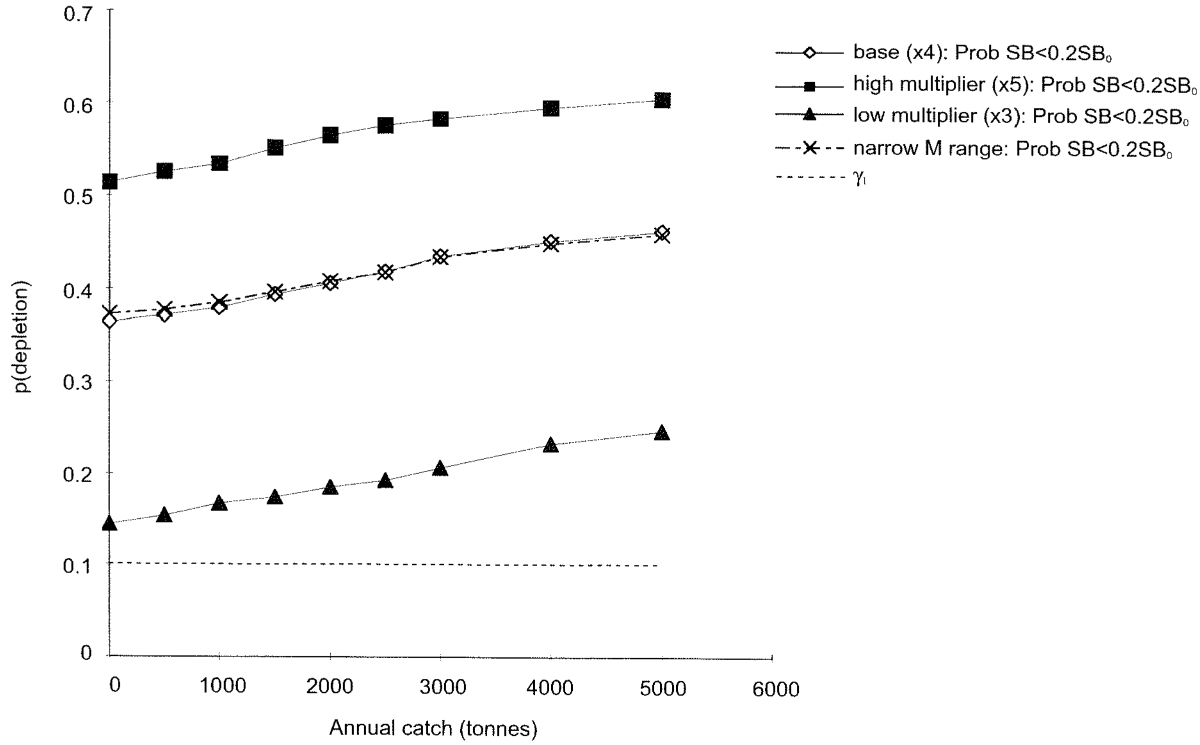

Figure 3: Probability of stock biomass dropping below 20% of the unexploited median level over a 10-year period (smoothed). CCAMLR's traditional γ_1 level is shown.

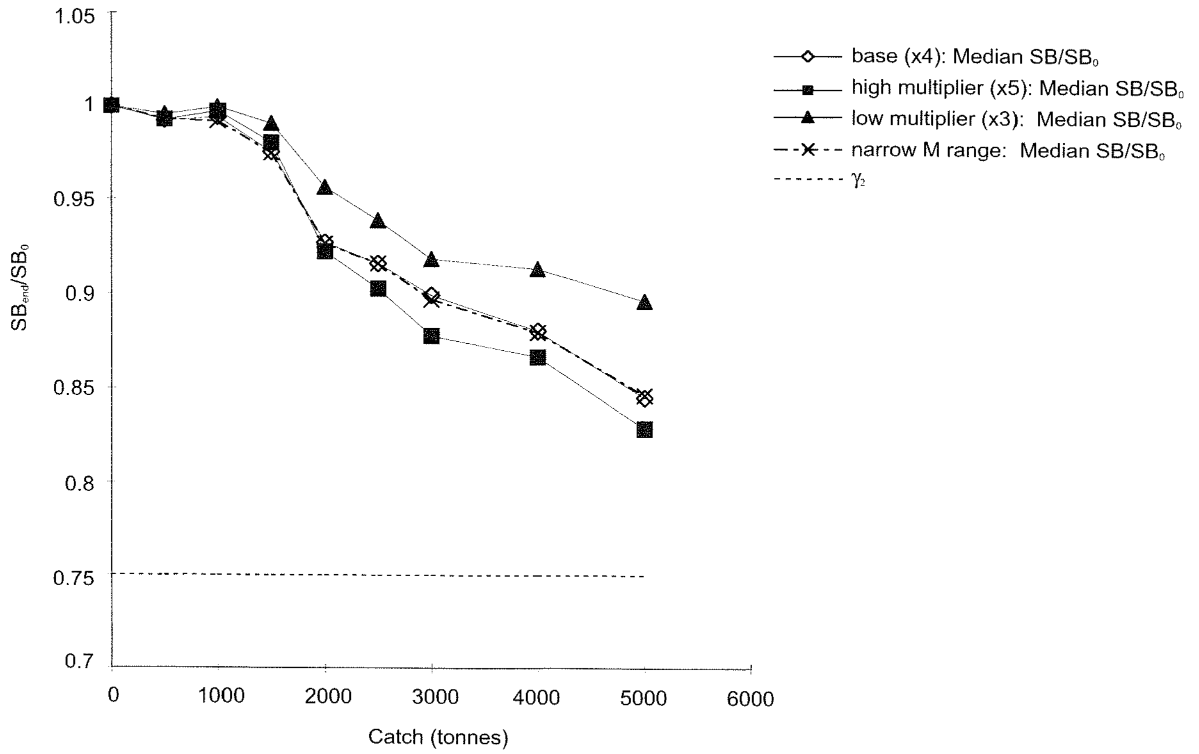

Figure 4: Ratio of median stock biomass after 10 years to median stock biomass in the absence of fishing (smoothed). CCAMLR's γ_2 level is shown.

Figure 3 demonstrates the primary feature of these simulations, the fact that even with zero catches there is a substantial probability of depletion of the population below 20% of its median unexploited biomass. This extreme variability is the direct result of the periodic increases in natural mortality in the model. It is also clear that as the multiplying factor for M increases, so does the probability of depletion of the population, even in the absence of fishing. The slope of regression of catch against the probability of depletion (p[depletion]) is 2.21E-5 for the base case, and the slopes for all other sensitivity runs in Figure 3 are not significantly different from this.

The response of the ratio of final to initial spawning stock biomass (SB_{end}:SB_0) to changing catches under the various simulations is shown in Figure 4. In contrast to the probability of depletion, the slope of SB_{end}:SB_0 against catch did change with the various sensitivity runs, so that the ratio of SB_{end}:SB_0 was lower as the multiplier of M increased. Over the range of catches shown in Figure 4, limited by considerations of CCAMLR's γ_1 criterion (Figure 3) rather than its γ_2 criterion, the γ_2 level of 0.75 was not reached. The catch level at which SB_{end}:SB_0 reached 0.75 in the base case was 7 150 tonnes.

DISCUSSION

It is clear that the very high variability in M and recruitment creates a situation where even under conditions of no exploitation the population often drops to less than 20% of the median unexploited biomass. As one would expect, increasing the maximum level of natural mortality also increases the probability that at some point in a 10-year projection the population will be depleted. However, the population does not usually stay depleted for long. For instance, although in 37% of base case runs spawning stock biomass dropped below 20% of the median B_0 level during the 10-year projection period, in only one-third of these was the spawning stock level less than 20% of the median level at the end of the run. Detailed examination of stock trajectories indicated that most of the time the stock is only depleted for one or two years. This behaviour is a direct result of the high levels of variability in recruitment, and the relatively low M in 'normal' years. Although this might change if a strong stock-recruit relationship were introduced, it seems to fit with our general understanding of fluctuations in *C. gunnari* abundance. Given this high variability, it is not surprising that the spread of uncertainty in the base level of M does not seem to have much effect.

The decision rules used by CCAMLR in the past do not seem to be appropriate for this stock. γ_2, the catch at which median SSB at the end of the 10-year fishing period is 75% of the median in the absence of exploitation, appears to be workable (Figure 4) although the rationale for choosing 75% is open to question. Uncertainty surrounding precise predator demands and prey-switching in times of krill scarcity, and the high variability of B_0, make direct calculations of an appropriate level for γ_2 impossible at the moment.

In contrast, γ_1, the level of catch at which the probability of SSB dropping below 20% of its unexploited median value is 0.1, is exceeded in all the scenarios considered here and does not seem workable. De la Mare et al. (1998) also encountered this phenomenon when considering long-term yields for *C. gunnari* around Heard and McDonald Islands, and have suggested as a solution a modification to the rule. In cases like this they suggest that γ_1 should be the catch level where the probability of depletion increases by 0.05 over the probability in the absence of exploitation. Figure 5 presents our results in terms of this increase, suggesting a sustainable catch of about 2 500 tonnes. However, it does not seem to solve the problem. Because the slopes of the lines in Figure 3 are equal, this rule is insensitive to the multiplier of M. On the other hand, the actual probability of depletion is highly sensitive to that multiplier and, intuitively, the higher variability caused by the high multiplier should lead to lower allowable catches.

A possible modification of this rule which would be sensitive to the level of depletion probability could be to set γ_1 at the catch where the probability of SSB <u>not</u> being depleted is reduced by 10%. For example, from Figure 3 in the base case the probability of the stock not being depleted is about 0.64 in the absence of fishing. Reduction by 10% would mean a target probability of not being depleted of 0.58. This corresponds to a probability of depletion of 0.42, which from Figure 3 is at a catch of about 2 900 tonnes. This allowable catch would drop to 1 500 tonnes in the scenario with the M multiplier of 5.

While this alternative γ_1 rule has its attractions, modifications of an accepted decision rule are not particularly desirable, especially when they appear to be increasingly arbitrary. The real

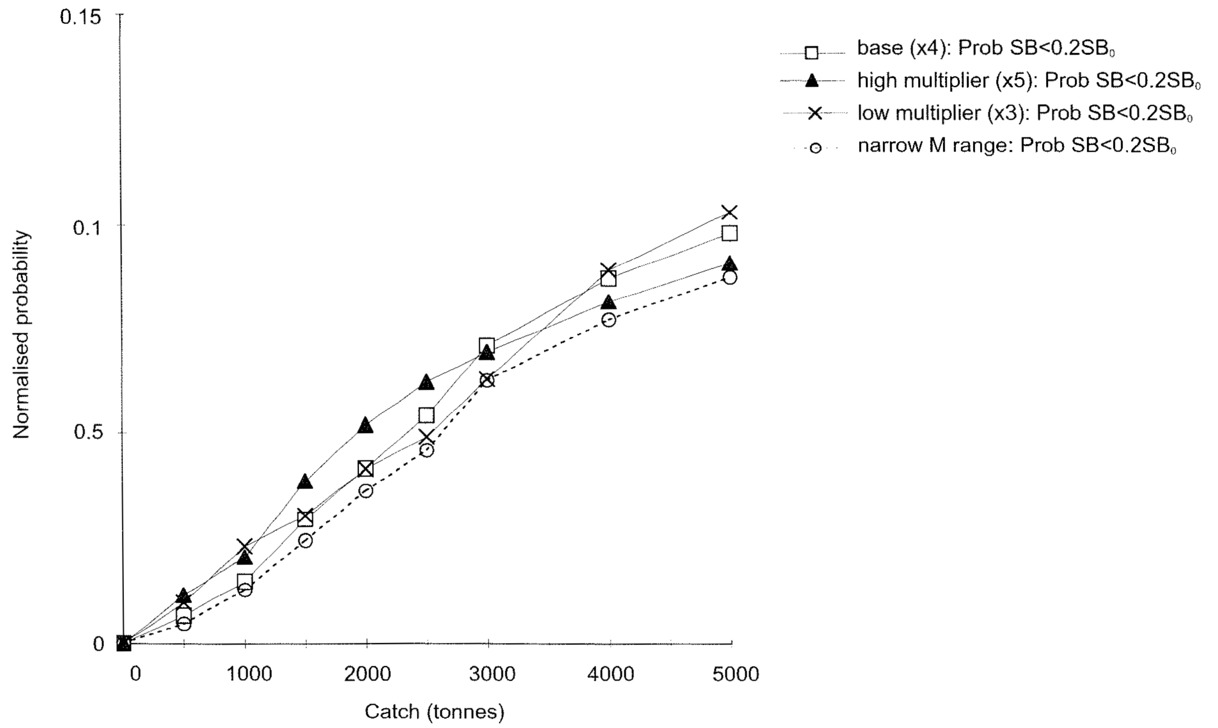

Figure 5: Probability of depletion of SB over a 10-year period, normalised to the probability in the absence of fishing (smoothed).

difficulty comes from attempting to use a long-term catch scenario with such a highly variable stock. We have used the GYM here to attempt to create a basis on which the general scheme of Figure 2 can be laid. While it confirms that a very low level of catch might be taken on an annual basis without further reference to biomass surveys, it has also confirmed that this is not a particularly suitable model or set of decision rules on which to manage *C. gunnari*. What is required is a new approach, based on the scenario in Figure 2, which sets out a management strategy that is more appropriate to the particular dynamics of *C. gunnari* populations and their relationships with the other major ecosystem influences.

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